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Performance Modeling of Agent-Aided Operator-Interface Interaction for the Control of Multiple UAVs

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Abstract – *The control of multiple Uninhabited Air Vehicles (UAVs) is operator intensive and can involve high levels of workload. Feedback from operators indicates that improvements in operator interfaces would reap significant gains in system performance and effectiveness. Incorporating automation agents in UAV control stations has been proposed as a solution to reduce workload and improve overall human-machine performance. This research investigated the efficacy of agent-aided operator interfaces in a scenario that involved multiple UAVs with the interfaces modeled as part of the UAV tactical workstations of a maritime patrol aircraft. A performance model was developed to compare the difference between mission activities with and without agent aids that was reflected in task conflict frequency, number of ongoing tasks, and task completion time. The simulation results revealed that agent-aided interfaces permitted operators to continue working under high time pressure, resulting in critical tasks being achieved in reduced time.*

Keywords: UAV control, operator interface, automation agent, performance modeling, human-machine interaction.

1 Introduction

The emergence of UAVs as useful and effective military systems is upon us. These new platforms have been introduced to the Canadian Forces (CF) to improve intelligence, surveillance, and reconnaissance capabilities. However, such platforms may provide vast amounts of data and the management of this data to provide situational awareness and support effective human decision-making is still an issue. Various levels of automation agents as operators' aids have been suggested to address the problem. An Intelligent/Adaptive Interface (IAI) is a potential technology for reducing operator workload and improving decision effectiveness in the employment and operation of these platforms. IAIs are human-machine interfaces that aim to improve the efficiency, effectiveness, and naturalness of human-machine interaction by acting adaptively and proactively to external events based on internal requirements. Specifically in the context of UAV control, an IAI is driven by software agents that support the decision-making and operators' action requirements under different levels of workload and task complexity by presenting the right information or action proposals, or perform actions, at the right time. Such technologies are likely to be integrated into many future CF systems.

Defence Research & Development Canada (DRDC) has initiated a multi-year program for the development of IAIs for advanced UAV control for the Air environment. The aim of this program is to develop, demonstrate, and prioritize enabling technologies that can be applied to advanced operator interfaces that will support reduced manning and enhanced performance in complex military systems, particularly multiple UAV control from an airborne platform. This program will also produce preliminary design guidelines for IAIs.

The DRDC program has three phases: IAI concept development, interface prototyping, and experimentation. The work reported here is a summary of operational analysis and simulation results of the first phase in which the focus was to investigate the efficacy of IAIs in an operational situation. The selected environment involved CF maritime aircraft operations in support of counter-terrorist activities. The operator interfaces within which the IAIs were modeled using task network analysis techniques were on the tactical workstations of a modernized maritime CP140 patrol aircraft. The augmented CP140 crew took over the UAV operation in the role of UAV Pilot (UAV Plt), UAV Sensor Operator (UAV Senso), and Tactical Navigator (TACNAV) in the back end of the aircraft.

Research on IAI in the military research and development community was limited when this work was done. As a result, this project began with a Hierarchical Goal Analysis (HGA) within which standard mission, operation, and goal analysis procedures were followed to gain more detailed understanding of implementation issues and opportunities for IAI. Following the positive results reported herein, a detailed and focused literature review [1][2][3] was conducted and will be reported in a separate paper. This paper starts with the methodologies used for operational analysis and performance modeling. Then, the rest of the paper discusses the simulation results and the implications of the potential IAI functions for the control of multiple UAVs.

2 Methodology

The starting point for the design of any complex system should be analysis. For systems where human functions are predominantly "cognitive", the method of analysis should capture this essential human activity. It is likely that advanced UAV control systems will require operators to interact with automated systems such as IAIs. IAIs are sophisticated and will require knowledge about mission goals, the operators' goals and states, as well as environmental states. The methods of analysis used in this research were based on Perceptual Control Theory (PCT) [4]. Hendy et al. [5] suggested analyzing operations/missions as hierarchies of goals, nested, sequenced or otherwise linked into logical networks, which could then model and predict activities. Classic task analysis techniques teamed with current PCT and HGA in this research.

The analytical effort commenced with the development of a multiple UAV command and control scenario from which individual and team goals were generated at successively deeper levels of decomposition. Each goal was associated with a PCT control loop from which multiple tasks (or behaviours) were spawned, each with related lower level goals. At the lowest level, all operator tasks which influence the "world", were logically connected as an Operational Sequence Diagram (OSD) to support the upper level goal. Groups of OSDs were connected to achieve even higher goals. The resulting hierarchy of task networks was modeled in the Integrated Performance Modeling Environment (IPME), and workload, goal completion times and other supporting data were produced. The task network model was run in two modes: one assuming the operators used an interface without automation agents and the second assuming interface automation used IAI agents. The difference between mission activities without automation agents (IAI OFF) and with automation agents (IAI ON) was reflected in task conflict frequency, number of ongoing tasks, and the time to complete critical task sequences. Hence, the objective of this work was to produce a HGA and a task network model based on the mission scenario that involved controlling multiple UAVs from an airborne CP140. The network model was used to evaluate the IAIs during scenarios involving increasing levels of workload.

2.1 Operational Mission Scenario

Like a task analysis, an HGA requires an operational scenario and the creation of a decomposition of goals from the scenario. In order to understand mission goals, an *Operational Mission and Scenario Analysis for Multiple UAVs Control from An Airborne Platform* has been conducted as a fictitious counter-terrorist security arrangement [6]. As a prerequisite in the analysis, a one-hour scenario was developed with extensive Subject Matter Expert (SME) sessions. Three SMEs were CF individuals who were involved with the CF UAV exercise programs and have extensive CP140 and UAV operational experience. The scenario was a minute-by-minute description along with plots of the mission evolutions. It involved an ongoing fisheries patrol, and approximately 200 vessels have been plotted in the vicinity of the nose and tail of the Grand Banks Canada. A CF patrol frigate was on-scene with two Vertical Take-Off UAVs (VTUAVs) and a maritime helicopter. Overhead, there was a CP140 patrol aircraft equipped with 16 Mini-UAVs and its own sensor suite. A Medium Altitude Long Endurance (MALE) UAV was also on-scene under the control of the Regional Operations Centre (ROC) located in Halifax. Therefore, there were a number of mini-UAVs, two VTUAVs, and one MALE UAV in the scenario.

The CP140 UAV tactical crew (i.e., TACNAV, UAV Senso, and UAV Plt) had responsibility for controlling UAV assets. The TACNAV occupied his normal position, and to the left of the TACNAV were the UAV Op and UAV Plt, as illustrated in Figure 1. The TACNAV was given the most complex role as the UAV team leader. Besides coordinating the broader crew on board the CP140, he was primarily responsible for understanding the overall tactical situation, planning appropriate responses to that situation, and delegating work to the other two UAV members of the crew in order to affect those responses. The UAV Plt was given the least complex role in that he was responsible for the safe and appropriate conduct of all UAVs under the crew's control. He might be required to flight plan individual UAVs, but the TACNAV was ultimately responsible for that task. The UAV Senso was responsible for managing the information being returned by the sensors onboard the UAVs under the crew's control, and for relating findings based on that sensor data back to the rest of the crew, as appropriate. The result was that there existed an environment to assess the efficacy of IAI across three levels of workload and job complexity, respectively.

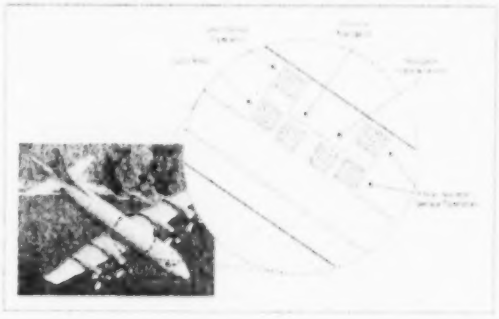


Figure 1. UAV crew positions in CP140 compartment

2.2 Operational Sequence Diagrams

By using symbology to indicate actions, inspections, data manipulation (i.e., transmission, reception, and storage), time delays, and decisions, OSDs show the flow of information and operator functions through the system in relation to the mission timeline. They can graphically illustrate the logical interconnection of operators' tasks and the flow of information throughout the system during the conduct of the mission scenario. This visual representation of the task network is suitable for HGA review and the generation of network models. Thus, OSDs are particularly useful for the analysis of highly complex systems which require many time-critical information-decision-action functions by multiple users, the case for this study.

With the scenario written, a series of OSDs were prepared to facilitate a function and goal/task analysis of the envisaged system and the development of a model from which performance predictions could be made and the potential for IAI automation agents identified. These OSDs also created an inventory of all bottom-up lowest level tasks in a temporal sequence. Figure 2 illustrates a small portion of an OSD as an example of the operational network between three UAV operators.

2.3 Hierarchical Goal Analysis

Combining function and task analyses into a single process, HGA is rooted in PCT, and is therefore based on the idea that human and machine activities can be described in terms of a hierarchical control model. The PCT model suggests a multi-layered system, with multiple goals providing the reference points for a hierarchical organization of control loops. All control loops involve a variable that is influenced. If there is a goal or objective, there must be a variable that is influenced. In PCT terms, variables/goals must be defined in perceptual terms (e.g., the operator will achieve the goal when they perceive that "the counter-terrorist mission has been completed").

A particular interest in this work is the identification of goals that are candidates for IAI automation agents. Upon the completion of the scenario and OSDs, a hierarchical decomposition of the envisaged system goals was conducted. The goal decomposition for all three UAV operators took place according to a means-end hierarchy and the needs of analysis were typically satisfied at the fourth or fifth level in this exercise. The goal decomposition was first performed in a top-down fashion first from the highest level (e.g., GOAL= counter-terrorist mission is completed) down to lower and lower levels (e.g., GOAL= VTUAV sector search is planned). Then, a more stringent bottom-up approach was completed with the study of the detailed mission activities in OSDs. As a result, more goals were added in the list of the top-down analysis to completely generate the HGA inventory. Table 1 illustrates an example of a small portion of HGA results.

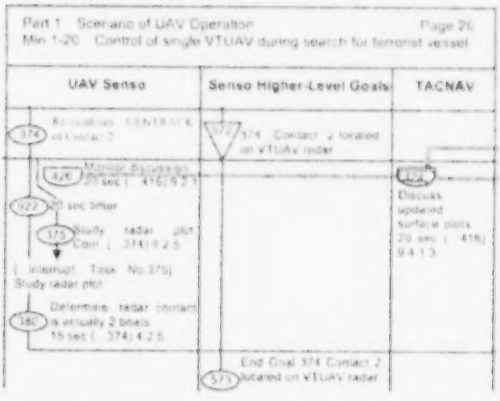

Part 1 Scenario of UAV Operation
Page 26
Min 1-20 Control of single VTUAV during search for terrorist vessel
UAV Senso
Senso Higher-Level Goals
TACNAV
374 Contact 2 located on VTUAV radar
Discuss updated surface plots 20 sec (...416) 9.4.1.3
20 sec timer
Study radar plot Com (...374) 4.2.5
Interrupt Task No 375) Study radar plot
Determine radar contact is actually 2 boats 15 sec (...374) 4.2.5
End Goal 374 Contact 2 located on VTUAV radar

Figure 2. An example of operational sequence diagrams

Table 1. A portion of hierarchical goal analysis

Number	Level					Goal/Objective and Sub-goals/Sub-objectives	IAI Candidate	Influenced Variable	Assignment	Completion Time (Sec)
	1	2	3	4	5					
Top	I want to perceive the (...) conduct of the terrorist patrol mission									
9	... communications are conducted and maintained									
9.1		... directions (instructions) are received								
9.1.1			... directions are received from other crew members				Yes	Directions	UAV Plt	4 to 25
9.1.2			... directions are received from other units				Yes	Directions	UAV Plt	5 to 14
9.2		... information is received								
9.2.1			... information is received from other crew members							
9.2.1.1				... VTUAV refuelling location				Location	TACNAV	5
9.2.1.2				... VTUAV calculated time on task			Yes	Time	TACNAV	5
9.2.1.3				... the flight crew's message that contact is identified				Message	UAV Senso	5

2.4 Identification of IAI Automation Agents

In order to compare interfaces with and without IAI assistance, it is necessary to identify candidate tasks/goals for IAI automation. Following the generation of OSDs and the HGA, goals related to a system that can be automatically operated (with automation intelligence or expert knowledge) were chosen to be appropriate IAI automation agents. Therefore, goals for which the system would have no information of automated operations could not be identified as IAI automation tasks. For example, an incoming verbal tasking from the ROC could hardly result in the initiation of an IAI task because the CP140 system would not be aware of the contents of the message. On the other hand, the system would track key-strokes and cursor movement and would be able to deduce that an operator was attempting to complete multiple concurrent tasks. In this case, the interface could adapt to the situation and provide partial or complete assistance to the overworked (over-tasked) operator. For example, the interface may include provision of potential UAV search patterns if the busy operator has UAVs airborne and un-tasked due to high operator workload. Hence, route planning automation agent was chosen as the first type of IAI tasks.

The second type of tasks chosen as IAI agents were communication tasks for which information regarding the upcoming communication was available to the IAI sub-system. In general, verbal communications amongst the crew are preferred, providing that the crewmembers are not over-tasked. However, when a commonplace communication is initiated which interrupts the recipient while that person is engaged in a complex cognitive task, the communication is detrimental. As a result, during high workload periods and when the data is available for the system to facilitate communications, an "intelligent communication agent" should augment or facilitate transfer of directions or information. For example, based on the HGA results it was determined that whenever the TACNAV inserted a fly-to waypoint for a UAV which was just about to be launched, he would advise the UAV Plt that the waypoint was inserted and gave the general location of the waypoint. During low workload periods, this transfer of information is good to accomplish verbally because the TACNAV can immediately verify that the UAV Plt understands and is in agreement with the tasking. During high workload periods, this message may be lost, forgotten, or misinterpreted. It has been assumed that, for the purposes of this study, the IAI agents would initiate the communication by setting a flag with the information on the TACNAV's workstation that would be sent when the TACNAV initiates transmission with the touch of a function key. This stimulus-response TACNAV task would be non-intrusive and would transfer this internal IAI message to the UAV Plt for him to review at his earliest opportunity and without interference.

2.5 Task Network Modeling

Following the conduct of the HGA and identification of IAI agents, a task network model was developed in IPME. IPME is a discrete event simulation framework used to model and assess human and system performance [7]. It is comprised of an environment model, a crew model, a task network, a performance-shaping model, and optional external models. Combined with IPME's scheduling algorithm, these models can help an analyst predict workload and operator performance. The IP/PCT mode uses an algorithm and an information processing scheduler to adjust operator performance based on various factors such as time pressure, task criticality, and task conflicts. The analysis was completed using the IP/PCT mode of IPME.

2.5.1 IPME Network Model Development

An IPME database was generated while producing the HGA and OSDs. In the database, each goal was allocated to an operator or a system with a descriptive label. With the database, a sequential type of operational network model was developed. Although the network model was a UAV operator model, external events (other aircrew activities, UAV activities, and other unit activities) had to be established to allow the network to function as a closed-loop feedback system. These were prepared and included in the network.

In the model, a task network was created following the structure of the HGA. The network was used to define task behavior, operator assignment, and interactions between tasks and operators. By linking together various networks or tasks, the model attempts to replicate the behavior of a real system. The definition of the behavior of each individual task was done through the various tabs, the function list, and the variable/goal database of IPME. The model was run in IP/PCT mode and data were collected once with automation agents (IAI ON) and once without (IAI OFF).

2.5.2 Simulation Output and Measurements

IPME contains built-in data collection and reporting capabilities. The data collected were used to analyze the model's (operator's) behavior and determine the effects of using IAI agents on the operator's performance. Since the model was developed to compare missions conducted with and without IAI agents, measurements of effectiveness and performance had to provide a means of assessing the merits of incorporating these new technologies. In addition, the measures had to give a clear indication of the most fruitful areas for further research and development. Furthermore, since this was the first opportunity to incorporate a full PCT evaluation of two design options involving differing levels of interface complexity, the measurements had to allow the merits of the PCT to be fully exercised.

The simulation output consisted of plots of two variables normalized against the mean mission timeline. The term "normalized" means that the respective plot of each of the 10 runs of the model is temporally adjusted to match the mean mission time. The first variable is Task Conflict Frequency, which is defined as, for each run, the percent of time during a sliding one-minute window that the operator must interrupt or delay a task. The second variable plotted is the Number of Ongoing Tasks, which gives the average number of ongoing operator tasks with significant cognitive components. Besides these two plots, the other output is Goal Completion Time for critical tasks (higher-level goals in HGA). It was also chosen as a means to determine not only how an IAI system would affect an operator's ability to achieve an objective, but also how the IAI system improved the operator's performance. These three measurements are both operationally relevant and technically feasible.

3 Results and Discussion

After running the IPME model ten times with IAI automation mode ON and OFF, data were collected and analyzed for the three measurements. Figures 4 and 5 provide sample outputs of the two plot types: task conflict frequency and number of ongoing tasks. Figure 6 provides a sample output of higher-level goal completion time.

Figure 4 shows that with IAI mode selected ON, the operators were dealing with fewer task conflicts (17%) comparing to IAI OFF mode (38%) around 14 to 15 mins. Figure 5 shows, for a different portion of the scenario, that with IAI mode selected ON, the operators were not dealing with significantly different number of ongoing tasks comparing to IAI OFF mode. However, it was clear that the mission evolved much faster with the IAI selected ON (from 15 mins to 12.3 mins), which clearly indicates an advantage in that the use of IAI resulted in reduced goal completion times and thus left more time for planning and problem solving. The reduced goal completion times were also evident in Figure 6 that provides the results of 9 out of 38 higher-level goals in the third part of the scenario, which contained the highest workload for the UAV crew. These goals were the ones influenced temporally by tasks related to the two IAI functions modeled (i.e., crew communication and route planning). It indicates that the greatest advantage of using the IAI mode of operations appears to be a reduction in the time required to complete higher-level goals. For example, the scenario involved planning the deployment of 3 Mini UAVs. The time to complete this activity was modeled to be a reduction by more than 50% (goal number 4 in Figure 6).

The results shown in Figures 4 and 5 indicated that the UAV tactical crew in the simulation maintained a constant intensity of activities throughout the various levels of increasing workload and role complexity. This was anticipated because the network assumed trained operators would operate at a steady and consistent level. The difference between mission activities with automation agents (IAI ON) and without (IAI OFF) was reflected in the time to complete critical task sequences (higher-level goals). With goals that required planning the UAV flight paths or search patterns, reduced times were found using the IAI to assist the operator. The automation was evidenced through the interface anticipating the users' activities in high-workload situations and offering pre-calculated routes for the operator to accept or modify.

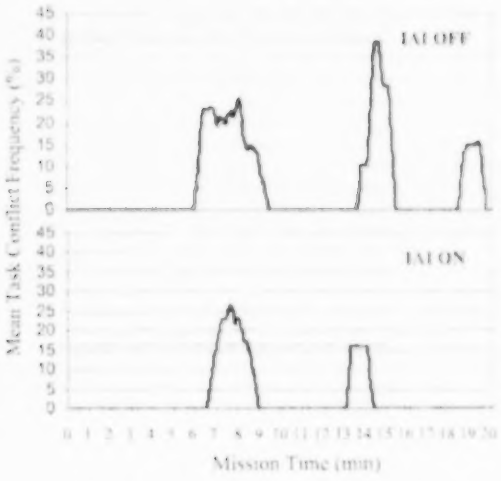


Figure 4. A sample output of task conflict frequency.

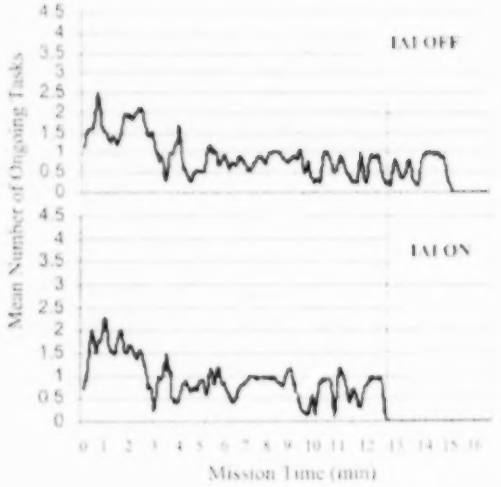
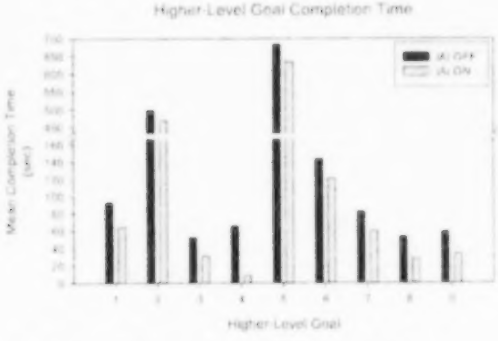


Figure 5. A sample output of number of ongoing tasks.

All goals that required intense verbal communications within the crew were also assisted using the IAI mode. IAI automation agents were modeled to anticipate the communication requirements and facilitate internal tasking and information transfer using an "intelligent communications agent". This agent proposed messages at opportune times and, without auditory distraction, passed the internal communication to the appropriate individual(s). Similarly, non-distracting feedback that the message had been received was modeled.



Goal 1: Crew is briefed on the response to the loss of VTUAV 1
Goal 2: Handover of VTUAV 2 is completed
Goal 3: Mini UAVs 2 to 5 are readied for launch
Goal 4: Deployment of Mini UAVs 2 to 4
Goal 5: Mini UAV 5 is employed over downed VTUAV 1
Goal 6: Control of the Laser UAV is established
Goal 7: Reassessment of need to attack terrorists is completed
Goal 8: Search for the Lethal UAV is discussed and search plan is initiated
Goal 9: UAVs are set to autonomous mode for CP140 to commence search

Figure 6. An example of completion time comparison for higher-level goals with and without IAI

4 Conclusions

The control of multiple UAVs from an airborne platform is a cognitively complex task with high workload, but using IAI automation agents in these advanced systems will likely provide a real potential for improvement in the effectiveness of UAV operators. The simulation conducted using the task network analysis technique in IPME provided numerical evidence of improved performance with IAI agents used. As expected from the preliminary analyses, the great advantage of the IAI-aided operations appears to be a reduction in the time required to complete critical tasks or higher-level mission goals. This is complimented by modest reductions in task conflict frequency and the reduction in the number of tasks interrupted, delayed, or shed.

Although the IAI tasks identified in this simulation study (e.g., router planner and communication agent) could only be considered as initial estimates of augmented cognition/decision aids, further analysis regarding the most beneficial tasks to modify is recommended. Additionally, it is important to focus on an experimental design necessary to test the efficacy of IAI based operator-interface interactions conducted in this study. Furthermore, considerable effort may be required to implement IAIs into prototype systems, and strong empirical evidence would be important to substantiate this effort.

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